A Multi-Center Space Data System Prototype Based on CCSDS Standards

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Abstract— **Deep space missions beyond earth orbit will require new methods of data communications in order to compensate for increasing Radio Frequency (RF) propagation delay. The Consultative Committee for Space Data Systems (CCSDS) standard protocols Spacecraft Monitor & Control (SM&C), Asynchronous Message Service (AMS), and Delay/Disruption Tolerant Networking (DTN) provide such a method. However, the maturity level of this protocol stack is insufficient for mission inclusion at this time. This Space Data System prototype is intended to provide experience which will raise the Technical Readiness Level (TRL) of this protocol set.**

In order to reduce costs, future missions can take advantage of these standard protocols, which will result in increased interoperability between control centers. This prototype demonstrates these capabilities by implementing a realistic space data system in which telemetry is published to control center applications at the Jet Propulsion Lab (JPL), the Marshall Space Flight Center (MSFC), and the Johnson Space Center (JSC). Reverse publishing paths for commanding from each control center are also implemented. The target vehicle consists of realistic flight computer hardware running Core Flight Software (CFS) in the integrated Power, Avionics, and Power (iPAS) Pathfinder Lab at JSC.

This prototype demonstrates a potential upgrade path for future Deep Space Network (DSN) modification, in which the automatic error recovery and communication gap compensation capabilities of DTN would be exploited. In addition, SM&C provides architectural flexibility by allowing new service providers and consumers to be added efficiently anywhere in the network using the common interface provided by SM&C's Message Abstraction Layer (MAL).

In FY 2015, this space data system was enhanced by adding telerobotic operations capability provided by the Robot API Delegate (RAPID) family of protocols developed at NASA. RAPID is one of several candidates for consideration and inclusion in a new international standard being developed by the CCSDS Telerobotic Operations Working Group. Software gateways for the purpose of interfacing RAPID messages with the existing SM&C based infrastructure were developed. Telerobotic monitor, control, and bridge applications were written in the RAPID framework, which were then tailored to the NAO telerobotic test article hardware, a product of Aldebaran Robotics.

TABLE OF CONTENTS

1. INTRODUCTION

Spacecraft mission control centers are typically organized by agencies and missions. Generally, each center has unique interfaces to exchange mission services and products (Telemetry, Command, Planning, Navigation, Tele-robotics, and others.) These unique interfaces drive higher costs for integration and mission cross-support.

The CCSDS Mission Operations Spacecraft Monitor and Control Working Group has been addressing these issues by developing a set of standards for interoperability. These standards are in various stages of development by several international space agencies, including NASA. As standardized interfaces are included in mission operations centers, the cost for incorporating cross support and interoperability across agencies and missions will decline.

The Space Data System prototype described in this paper demonstrates the ability to leverage services and reuse investments from several different centers on any given mission. Telemetry and Command services were implemented at the Protocol Test Lab (PTL) at JPL, the Huntsville Operations Support Center (HOSC) at MSFC, and in the Operations Technology Facility (OTF) at JSC. This SM&C, AMS, and DTN based Space Data System (SDS) prototype was originally developed in the OTF in support of the OTF/German Aerospace Center Prototype [1] and the integrated Power, Avionics and Software (iPAS) [2] Pathfinder activities. In FY 2014, this SDS prototype was extended to support multi-center SM&C telemetry and command applications at JPL and MSFC.

2. SPACE DATA SYSTEM OVERVIEW

Figure 1 illustrates the general layout of this Space Data System prototype.

Telemetry in the form of CCSDS Space Packets originates with the Multi-Purpose Crew Vehicle (MPCV) Orion vehicle system in JSC Bldg. 29. Utilizing the Licklider Transmission Protocol implementation provided by the Interplanetary Overlay Network (ION) [3], the telemetry stream is sent to a Deep Space Network (DSN) Operations Center (DSOC) simulation in the JPL Protocol Test Lab. In the DSOC simulation, a 4 second one-way light time (OWLT) delay is applied, and 2% and 0.1% frame drop rates are modelled for the downlink and uplinks, respectively. The 4 second OWLT is variable and can be set to any value up to 30 minutes. The asymmetric frame drop rates reflect the effects of differing power levels and antenna sizes between the spacecraft and DSN ground sites. Utilizing the AMS implementation provided by ION, the telemetry stream is then distributed to SM&C consumer applications in the OTF at JSC, the HOSC at MSFC, and in the Protocol Test Lab at JPL. In this prototype, command messages from each center follow the reverse paths.

Two observations can be made at this point. First, this is the only known SDS prototype based on the combined SM&C, AMS, and DTN protocol stack. Second, this is a realistic prototype for potential future DSN automation based on Delay/Disruption Tolerant Networking.

3. SPACE DATA SYSTEM DETAILED DESIGN

Figure 2 illustrates the Space Data System detailed design.

A description of each segment follows.

Flight Computer Segment

Core Flight Software from the Goddard Space Flight Center runs on representative flight-like hardware in iPAS vehicle Bay 2, JSC Bldg. 29. An environment simulation generates sensor data, which is relayed through the flight computer to the onboard communications processor, referred to as "datapub2." The iPAS avionics suite contains an onboard power system, which processes commands relayed through the flight computer. A muffin fan is configured as the command target. Both telemetry and command data are formatted as CCSDS Space Packets, sent between the flight computer and the onboard communications processor and over Ethernet and the User Datagram Protocol (UDP).

Onboard Communications Processor Segment "datapub2"

The onboard SM&C provider and DTN processes are hosted on datapub2. The SM&C Parameter Provider process ingests the CCSDS Space Packet telemetry data from the iPAS flight computer. It then passes SM&C messages to the DTN process using the Asynchronous Message Service (AMS), which provides publish and subscribe functionality. AMS messages are then sent to the DSN Ops Center simulation at JPL using the Licklider Transmission Protocol

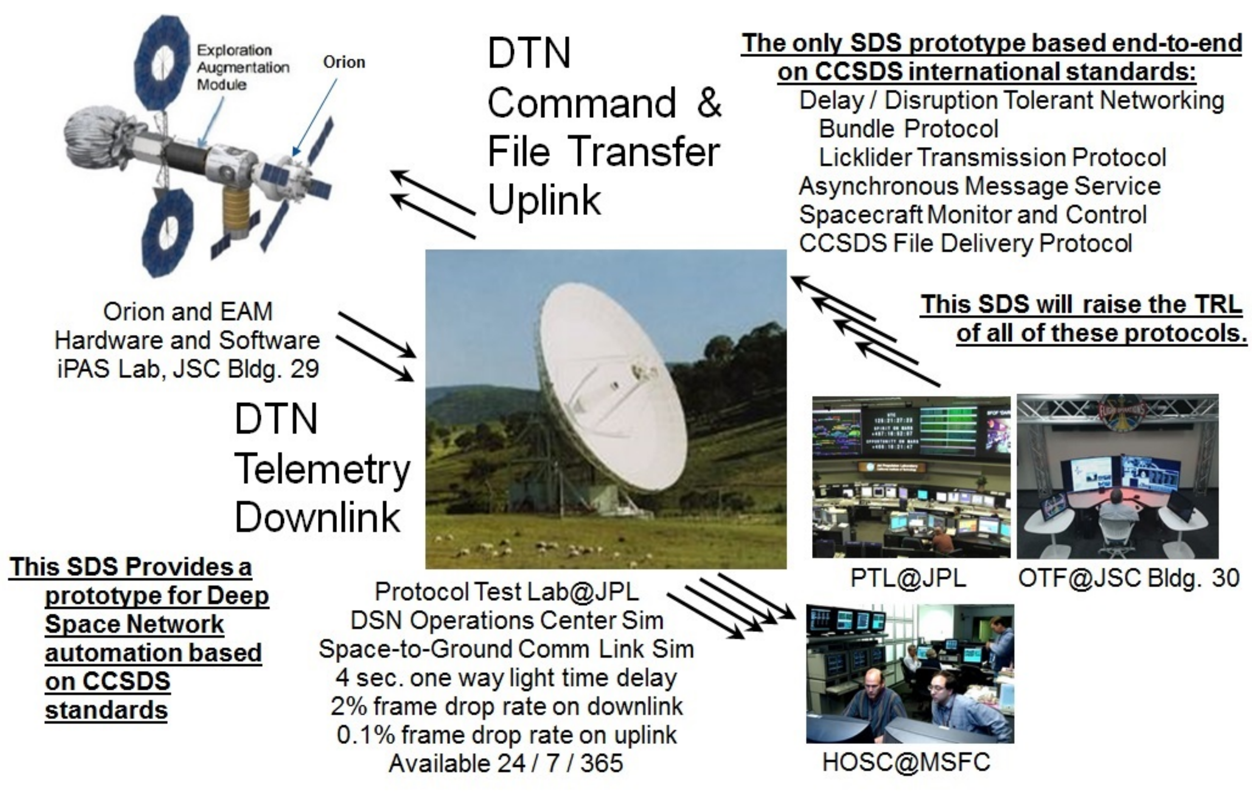

Figure 1. Multi-Center Space Data System Overview

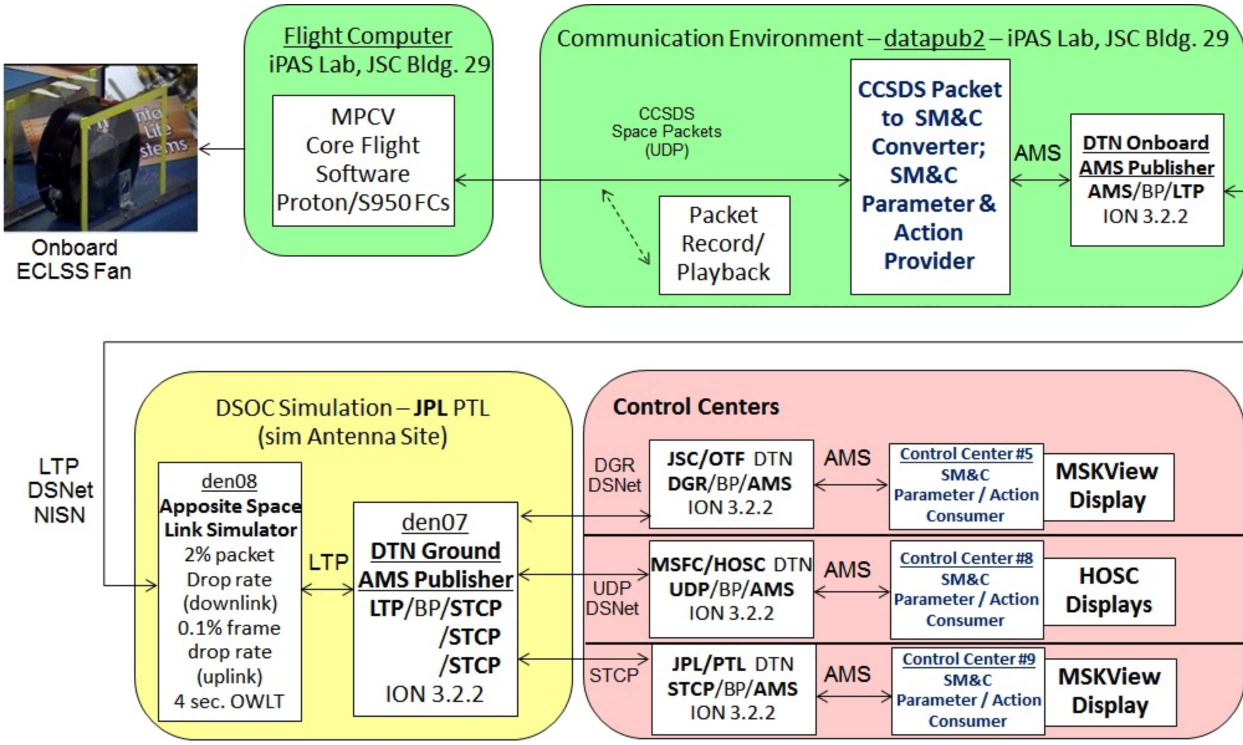

Figure 2. Multi-Center Space Data System Detailed Design

(LTP). LTP is a reliable connectionless protocol which provides automatic error detection and re-transmission. LTP is designed to support RF propagation delays on the order of interplanetary distances. The NASA Institutional Services Network (NISN) provides terrestrial connectivity.

The onboard communications processor "datapub2" also hosts the SM&C Action Provider, which receives command messages through the AMS/LTP/DTN ground-to-space link. The Action Provider generates CCSDS Space Packet command packets and forwards them to the flight computer for final relay to the onboard power system and the target muffin fan.

DSN Operations Center Simulation Segment

Two main functions are implemented at the DSN Operations Center simulation in the Protocol Test Lab at JPL. The first is the space-to-ground link model, which applies a 4 second OWLT delay, a 2% frame error rate on the downlink, and a 0.1% frame drop rate on the uplink.

The second main function of the DSOC simulator is to anchor the ground side of the AMS/LTP/DTN link, and to then re-publish the AMS telemetry streams for distribution to geographically dispersed control centers. Both Simple Transmission Control Protocol (STCP) and datagram retransmission (DGR) are used to provide reliable terrestrial links. DGR is explained further in reference [3]. Ground links over UDP are also supported.

Control Center Segment

The original set of SM&C control center applications was developed in the OTF. The applications interface directly with the DSOC distribution node at JPL. The applications are used to display telemetry and command history, as well as initiating commands to control the onboard target muffin fan.

These applications, as well as the SM&C interface software, were then sent to the Protocol Test Lab at JPL, where they were compiled and installed. Telemetry display and command functionality are transparent between the PTL and OTF control center applications. Telemetry displays are identical at both control centers, as well as command capability.

The same SM&C interface software was then sent to the HOSC at MSFC. In order to display telemetry, the HOSC "Display Dashboard" legacy application was fitted with the SM&C common interface. The capabilities to display telemetry and to easily add new parameters to the telemetry display were demonstrated. A new SM&C command application was developed, in order to generate onboard target fan actuation commands.

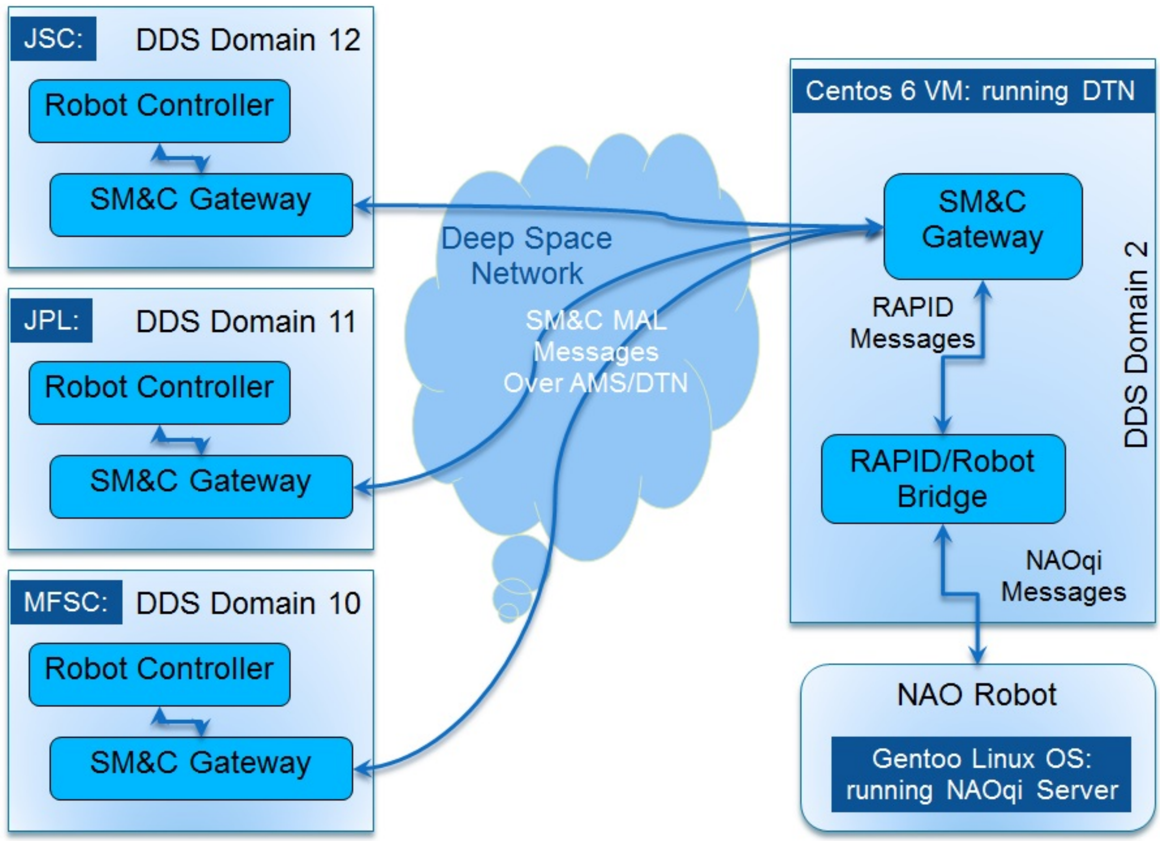

Figure 3. Multi-Center Telerobotics Architecture

4. TELEROBOTICS

Figure 3 illustrates the multi-center telerobotic control architecture.

A description of each segment follows.

Robot Controller Segments

The robot controller software module was developed in the Eclipse development environment, modified by JPL to include the Robot API Delegate (RAPID) telerobotic monitor and control protocols [4]. The controller consists of displays of robot joints and temperatures, battery charge level, and onboard camera views. The controller has the ability to command each joint separately, and to activate pre-programmed behaviors and postures. The controller includes the RAPID Access Control module, which is used to coordinate robot control authority between multiple centers. As Figure 3 shows, multiple instances of the robot controller can be executed simultaneously.

The Eclipse/RAPID development environment uses Data Distribution Service (DDS) as its transport layer. RAPID commands and telemetry are expressed as DDS messages.

SM&C Controller Gateway Segments

The SM&C controller gateway segments were introduced in order to interface the DDS based RAPID messages with the SM&C based Multi-Center Space Data System. The controller gateway simply encapsulates DDS messages into SM&C messages.

Deep Space Network Segment

The DSN segment is the Multi-Center Space Data System described in sections 2 and 3.

SM&C Bridge Gateway Segments

The SM&C bridge gateway extracts DDS messages from the SM&C messages transported over the DSN segment.

The RAPID/Robot Bridge Segment

The RAPID/robot bridge segment performs the final step of converting RAPID standard messages (over DDS) into robot specific commands, using the software development kit provided by the robot manufacturer.

5. OBSERVATIONS

This prototype is end-to-end, in that SM&C and AMS processes are executed onboard, as well as on the ground. The onboard SM&C and AMS processes impact both flight software complexity and flight computer resource utilization. A hybrid configuration is possible in which SM&C and AMS processes are restricted to ground resources.

This "all SM&C" configuration offers the advantage of architectural flexibility, in that SM&C consumer and provider applications can be utilized anywhere in the Space Data system, including onboard. This has been demonstrated in the iPAS, in which identical consumer applications have been executed in both onboard and ground-based processors.

This prototype SM&C, AMS, and DTN Space Data System has run continuously over the past two years. Weaknesses and improvement suggestions have been communicated to the developers. As the software has matured, system stability has improved. Unplanned outages have become rare.

6. SUMMARY

This project has shown that space mission information can be distributed to multiple control centers using standard Spacecraft Monitor and Control services. At the control center endpoints, local legacy applications can then be easily integrated into the SM&C and DTN infrastructure. When standard protocols such as SM&C and DTN are utilized, interoperability increases, and both per-mission and control center costs decrease. Since these are internationally standardized protocols, international interoperability can increase as well.

If SM&C functionality is extended to the spacecraft, then identical SM&C applications can be executed both onboard and on the ground. This would provide cost savings, avoiding separate development costs for both onboard and ground-based applications.

Interaction with the iPAS Pathfinder Lab has provided the opportunity to operate this multi-center Space Data System in a realistic scenario where light-time delay becomes significant. iPAS visibility has provided the opportunity to promote the acceptance and application of these internationally standardized protocols. This will contribute to raising their Technical Readiness Levels, and eventual incorporation into mission architectures and Deep Space Network re-design.

APPENDIX

A. ACRONYMS

AMS = Asynchronous Message Service
BP = Bundle Protocol
CCSDS = Consultative Committee for Space Data Systems
CFS = Core Flight software
DDS = Data Distribution Service
DGR = Datagram Retransmission
DSN = Deep Space Network
DSNet = Distributed Simulation Network
DSOC = DSN Operations Center
DTN = Delay/Disruption Tolerant Networking
ECLSS = Environmental Control and Life Support System
EAM = Exploration Augmentation Module
GSFC = Goddard Space Flight Center
HOSC = Huntsville Operations Support Center
ION = Interplanetary Overlay Network
iPAS = integrated Power, Avionics, and Software
JSC = Johnson Space Center
JPL = Jet Propulsion Laboratory
LTP = Licklider Transmission Protocol
MAL = Message Abstraction Layer
MPCV = Multi-Purpose Crew Vehicle
MSFC = Marshall Space Flight Center
NASA = National Aeronautics and Space Administration
NISN = NASA Institutional Services Network
OTF = Operations Technology Facility
OWLT = One Way Light Time
RAPID = Robot API Delegate
PTL = Protocol Test Lab
RF = Radio Frequency
SDS = Space Data System
SM&C = Spacecraft Monitor and Control
STCP = Simple TCP
TCP = Transmission Control Protocol
TRL = Technical Readiness Level
UDP = User Datagram Protocol

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This paper summarizes the achievements of the Multi-Center Space Data System Prototype team. The author wishes to acknowledge several individuals for their contributions. Pete Gonzalez/JSC provided the software engineering for the project; without his understanding of SM&C and the RAPID telerobotics protocol this project would not have been possible. Leigh Torgerson/JPL provided the space networking expertise for the DSN Operations Center simulation at JPL. Pat Donahue/MSFC provided the software engineering for the HOSC applications. Eric Wolfer/JSC and Jay Wyatt/JPL provided project management and funding. And finally, the late Lindolfo Martinez provided overall vision and guidance for this project.

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BIOGRAPHY

Thomas M. Rich *received a BSEE and an MEE in Electrical Engineering from Rice University, Houston TX in 1973 and 1974. He has been with contractor companies at JSC for more than 41 years, all in support of Space Shuttle flight control and flight planning systems in JSC Building 30, home of the Space Shuttle and International Space Station Mission Control Centers. He is currently the lead for the advanced spacecraft communication prototyping effort in the Operations Technology Facility (OTF), JSC Mission Systems Division. Prior to the OTF, he served as Integrated Planning System (IPS) system engineer for United Space Alliance. He was a certified navigation flight controller for STS-1, the first orbital flight of the Space Shuttle Program. His career started with developing onboard and ground based Space Shuttle navigation software at McDonnell Douglas Technical Services Company. He is presently a Senior System Engineer with Tietronix Software Inc., Houston TX.*